Trade openness and pollution in China: processing versus ordinary trade*

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Abstract

China's integration into the world economy was paralleled by a strong increase in environmental degradation. In this paper, we use recent detailed Chinese data on trade and pollution emissions to assess the local environmental consequences of China's trade integration. We ask how a city's greater trade openness affects the local Sulfur Dioxide (SO_2) emission intensity, one of the major sources of air pollution in China and a by-product of goods production. Our theory highlights a differential environmental impact of processing (assembly) versus ordinary trade, which is supported by the data. We take specific account of the endogeneity of trade and find that processing trade tends to reduce local SO_2 emissions. This is not the case for ordinary activities even though these today represent the main drivers of China's export and import growth. This result suggests some caution regarding pollution prospects in the context of the declining role of processing trade.

Keywords: Trade Openness, Pollution, SO2 emissions, China.
JEL codes: F10, F14, O14.

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1 Introduction

Over the past twenty years environmentalists and the trade-policy community have engaged in a heated debate over the environmental consequences of liberalized trade.[1] China, by having become the world's biggest exporter and in the same time experiencing serious environmental degradation, has helped intensify this debate.[2] Overall, disavowing the expectation of a pollution-haven effect, it seems that greater trade openness in China and in particular the development of assembly activities has accompanied the reduction in the country's emission intensity (Dean and Lovely, 2010). A growing literature has underscored the many ways in which assembly ("processing") and ordinary trade differ and how these differences affect China's economy (Amiti and Freund, 2010; Feenstra and Wei, 2010; Brandt and Morrow, 2017). However, it remains an open question whether these different regimes matter for the environment. This issue is particularly relevant as we are witnessing a turning point where China is showing its willingness to move up the value chain and no longer just be the assembly line of the world. If this is justified for reasons of employment and upgrading, it may have unfortunate repercussions in terms of its polluting emissions.

In this paper, we explore the link between international trade openness and pollution emissions in China by developing a simple theoretical model focusing on the differential environmental impact of processing and ordinary trade and estimating its main prediction on a panel of 234 Chinese cities.[3] We ask how a city's greater trade openness affects the local

[1] For an earlier review of the arguments see Copeland and Taylor (2004).

[2] China's greenhouse-gas emissions were about 30% of the world's total in 1990 (The Economist, 2013). The country has the world's highest annual incidence of premature deaths triggered by air pollution, which is estimated to represent a loss of about 3.8% in its yearly GDP (World Bank, 2007).

[3] As is common in the literature, we use the term city to refer to the whole prefecture, even though it includes both an urban and a rural part.

Sulfur Dioxide (SO_2) emission intensity, which is considered as one of the major sources of air pollution in China and a by-product of goods production.

Our analysis exploits a key characteristic of China's trade: the distinction between processing and ordinary trade. Processing trade refers to operations of firms, most often foreign-owned, which obtain intermediate inputs from abroad and, after assembling them in China, re-export the final products. Ordinary trade includes imports that are not destined to be incorporated into exported goods, or exports that did not rely specifically on imported intermediate inputs.[4]

We present theoretical and empirical arguments showing that a city's trade openness affects local pollution emissions differently when it concerns processing or ordinary trade, hence suggesting that production fragmentation plays a role in the environmental repercussions of China's enhanced outward orientation.

Our theoretical model predicts a different effect of trade liberalization on the environment for processing compared to ordinary trade. Our model extends the frameworks in Ethier (1982) and Krugman and Venables (1995) to examine linkages between local pollution and trade in intermediates. We find that the impact of opening up to trade depends on the respective intensity of labor versus domestic and foreign intermediate inputs. The model predicts a clear reduction in emission intensity for processing activities following trade liberalization. This environmental friendly effect comes from the decrease in wage rates and the number of domestic intermediates (which pollute locally). This helps substituting domestic intermediates for foreign intermediates and labor in the production process. Our

[4] In contrast to ordinary trade, China's processing regime confers substantial benefits on export processors such as the right to import duty-free raw materials, components, and capital equipment used in processing activity (Naughton, 1996).

model thus predicts an indisputable pro-environmental effect of the liberalization of assembly trade. However, the opposite is found in the case of the liberalization of ordinary trade. Our results nevertheless show that the negative impact will be lower if the cost share of imported intermediaries in the production process is limited. The intuition is that, in this case, trade liberalization will be less relevant.

We then bring our theoretical predictions to the data by using a panel of Chinese cities for the period 2003-2012. First, we investigate empirically the net effect of China's trade openness (combining ordinary and processing trade) on its emission intensity. Our results suggest that higher trade openness, defined as exports plus imports over GDP, has had overall a beneficial effect on the Chinese environment. This is in line with cross-country studies that have made use of exogenous determinants of trade to identify the causal effect of trade on the environment (Frankel and Rose, 2005; Chintrakarn and Millimet, 2006; Managi et al., 2009). Our results are robust to alternative indicators of pollution and more demanding specifications in terms of controls. From a quantitative point of view, the size of the effect is not negligible. A 1 percentage point increase in processing trade openness is estimated to have led to a fall in SO_2 emissions per capita of 7%.

We then estimate the main predictions of the model by distinguishing for each of the Chinese city between ordinary and processing and construct trade openness separately for each trade regime. We confirm the theoretical predictions and find a negative and significant effect of trade openness on emissions for processing trade. By contrast we find no significant environmental repercussions from ordinary trade activities. This lack of link between pollution and ordinary trade is reminiscent of Bombardini and Li (2019)'s results. They study the export expansion in dollars per worker in Chinese cities and suggest that it benefits health through a negative albeit insignificant effect on the concentration of pollutants locally. Their primary focus is however on the health outcomes of export expansions, and they do not consider the role of the international segmentation of production and environmental repercussions from trade depending on the different types of trade. Our results suggest that much greater environmental benefits can be uncovered when we consider the different modes of trade instead of considering trade openness in an aggregate way.

Our results are also consistent with Dean and Lovely (2010)'s finding that processing activities have contributed positively to the decline in the pollution intensity of China's trade.[5] The lack of comparable environmental benefits from ordinary trade is all the more a source of concern as ordinary trade has recently become the main driver of China's export and import growth. Our point estimates hence suggest some caution regarding local pollution prospects in the context of the declining role or processing trade in China.[6]

Our empirical approach also extends efforts to address endogeneity issues, which in general hinder the evaluation of the impact of trade on the environment (see Frankel and Rose, 2005; Managi et al., 2009).[7] Trade openness and the way in which trade policy is designed and enforced at the local level are likely to be correlated with other policies, including environmental policies and a variety of broader economic variables. We depart from the traditional use of cross-sectional data across a diverse set of countries, and exploit spatial

[5]The authors calculate the pollution intensity of imports and exports using industrial sector-level emission intensity. This pollution intensity is then weighted by the share of manufacturing exports (imports) corresponding to that sector and summed to yield an export (import)-weighted average pollution intensity for each year. Our work differs in that we exploit city-level data and compute exogenous sources of city-level trade openness, which provide us with an original instrumental-variable approach to address the endogeneity problems that are typical in this area.

[6]In 2002, ordinary trade represented 42.7 percent of China's total trade, but this share rose to 44.5 percent by 2007, and by 2012 had reached 52.1 percent.

[7]A large literature exists on the link in the opposite direction from the environment or environmental policies to trade, and faces the same empirical challenge (see Grossman and Krueger, 1993; Levinson and Taylor, 2008; Broner et al., 2012; Barrows and Ollivier, 2014).

and temporal heterogeneity in trade and pollution within a single country. This mitigates omitted-variable problems related to the difficulty of controlling for cross-country differences in national policies, legal systems and other institutions. Further, it reduces the traditional empirical difficulty that the environmental effects of trade are conditional on how local comparative advantage and environmental regulatory stringency compare to those in the rest of the world. Finally, it avoids the data-compatibility problems that are present in most cross-country analyses.[8]

The remainder of the paper is structured as follows. The next section outlines the theoretical framework. Section 3 sets out our empirical strategy. Section 4 then presents the data and some descriptive statistics while Section 5 discusses the empirical results. Last, Section 6 concludes.

2 Theoretical framework

We propose a simple model to analyze the effects of ordinary and processing activities on emission intensity. By their different nature, these two activities, called industries for simplicity, generate different emissions when trade openness changes.

We consider two countries, Home and Foreign, and three industries: two homogeneous final goods (ordinary and processing) and one differentiated intermediate good. Technologies are identical across countries and labor is the only primary factor of production. Production of the final goods does not pollute, while emissions are by-products of the production of the

[8]Two notable exceptions are McAusland and Millimet (2013) and Chintrakarn and Millimet (2006), which use data on intra-national and international trade for Canadian provinces and/or US states. They mostly focus on the differential effects of inter-regional versus international commerce. Our approach differs in that we focus on the largest developing country in the world. Also our data allow us to highlight the role of the international segmentation of production.

intermediate varieties. For the sake of simplicity, trade in final goods is free, but trade of intermediate varieties is subject to frictions that take the form of iceberg trade costs. Labor is perfectly mobile between the three industries within each country, but immobile across countries. We focus primarily on the Home economy. Foreign results are perfectly symmetric and marked by an asterisk.

2.1 Technology

Production takes place in two stages. We start our analysis by focusing on stage two.

Stage two: the final goods.

Production. The output of each final good, ordinary o and processing p, depends upon intermediates and labor, according to the following production technology:

$$Y_k = D_k^{\gamma_k} M_k^{\lambda_k} \ell_k^{1-\gamma_k-\lambda_k}, \qquad k = \{o, p\}\,,\ 0 < \gamma_k < 1, 0 < \lambda_k < 1, \tag{1}$$

where Y_k is the output produced using an aggregate of domestic intermediates, D_k, an aggregate of imported intermediates, M_k, and labor, ℓ_k. These production functions are increasing, concave and homogeneous of degree one in the inputs. The aggregate of domestic intermediate varieties is defined as follows:

$$D_k = \left(\sum_{\omega=1}^{n} d_{k\omega}^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \qquad \sigma > 1, \tag{2}$$

where $d_{k\omega}$ is the quantity of the intermediate variety ω domestically produced, and n is the number of domestic varieties. Similarly, the aggregate of imported intermediate varieties is defined as follows:

$$M_k = \left(\sum_{\omega^*=1}^{n^*} m_{k\omega^*}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{3}$$

where $m_{k\omega^*}$ is the quantity of the intermediate variety ω^* produced abroad, and n^* is the number of imported varieties. The production of final goods does not pollute and exhibits increasing returns with respect to the number of varieties, similarly to Ethier (1982). Taking prices of production factors as given, factor demands are derived from cost minimization:

$$\begin{aligned}
d_{k\omega} &= \frac{D_k p_\omega^{-\sigma}}{P_k^{-\sigma}}, \text{ with } D_k = \frac{\gamma_k Y_k}{\Gamma_k} P_k^{\gamma_k - 1} Q_k^{\lambda_k} w^{1-\gamma_k-\lambda_k}, \\
m_{k\omega^*} &= \frac{M_k \left(\tau_k p_{\omega^*}^*\right)^{-\sigma}}{Q_k^{-\sigma}}, \text{ with } M_k = \frac{\lambda_k Y_k}{\Gamma_k} P_k^{\gamma_k} Q_k^{\lambda_k - 1} w^{1-\gamma_k-\lambda_k}, \\
\ell_k &= \frac{\left(1-\gamma_k-\lambda_k\right) Y_k}{\Gamma_k} P_k^{\gamma_k} Q_k^{\lambda_k} w^{-\gamma_k-\lambda_k},
\end{aligned} \tag{4}$$

where p_ω is the producer price of the Home variety ω, $p_{\omega^*}^*$ is the producer price of the Foreign variety ω^*, and $\tau_k > 1$ is the iceberg trade cost incurred to import an intermediate variety to be used in the production of the final good $k = \{o, p\}$. Furthermore, $P_k = \left(\sum_{\omega=1}^{n} p_\omega^{1-\sigma}\right)^{\frac{1}{1-\sigma}}$ is the price index of the aggregate of domestic intermediates, and $Q_k = \left[\sum_{\omega^*=1}^{n^*} \left(\tau_k p_{\omega^*}^*\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$ is the price index of the aggregate of imported intermediates. Labor mobility between industries ensures a unique wage rate in a country, w in Home and w^* in Foreign. Finally, $\Gamma_k = \gamma_k^{\gamma_k} \lambda_k^{\lambda_k} \left(1-\gamma_k-\lambda_k\right)^{1-\gamma_k-\lambda_k}$ is a strictly positive constant. Given the demand for the production factors in (4) the total production cost is equal to

$$C_k = P_k D_k + Q_k M_k + w\ell_k = \frac{Y_k}{\Gamma_k} P_k^{\gamma_k} Q_k^{\lambda_k} w^{1-\gamma_k-\lambda_k}. \tag{5}$$

Firms spend constant shares, respectively γ_k and λ_k, of their total costs C_k on domestic and imported intermediates.

Ordinary versus processing production parameters. Recall that one final good is produced under the ordinary trade regime (subscript o), and the other one under the processing trade regime (subscript p). That difference is first reflected through the production function parameters. As the activity in the processing good industry is mostly assembling, the value added created in this sector is likely to be lower than in the ordinary good industry, that is $\gamma_o + \lambda_o < \gamma_p + \lambda_p$. Labor intensity is hence higher in the ordinary sector than in the processing sector. Ordinary versus processing differences in parameters will play a role in the environmental impact of trade openness.

Stage one: the intermediate good.

In each country, a continuum of active firms produces under monopolistic competition the intermediate good with labor as the only factor or production. Each firm produces one unique variety of the differentiated intermediate good under increasing returns to scale. Polluting emissions are a by-product of the production of intermediate varieties. However, as in Copeland and Taylor (1994), firms can abate pollution by diverting an endogenously determined share θ of labor from the production activity to the pollution abatement activity. As a consequence, firms adopt cleaner technologies by reducing polluting emissions at the expense of labor input. Output q_ω and the emissions e_ω associated with variety ω are given by

$$q_\omega = \frac{(1-\theta_\omega)(\ell_\omega - a)}{b}, \tag{6}$$

$$e_\omega = (1-\theta_\omega)^{\frac{1-\alpha}{\alpha}} q_\omega, \tag{7}$$

where ℓ_ω is the labor input, a is the fixed cost of production, and b is the constant marginal cost. The expression $(1-\theta_\omega)^{\frac{1-\alpha}{\alpha}}$ is the emission intensity of production. The parameter α is equal across firms and lies strictly between 0 and 1, so that an increase in the share of labor assigned by the firm to the abatement activity induces a decrease in its emission rate. From (7) it is readily observable that a firm has two non-exclusive options to reduce its emissions: either to reduce its production level q, or devote more labor to pollution abatement activity θ. From Equations (6) and (7) the production function can be formulated as

$$q_\omega = \left(\frac{\ell_\omega - a}{b}\right)^{1-\alpha} e_\omega^\alpha. \tag{8}$$

Pollutant emissions can then be treated as a by-product or as an input for the production of intermediate varieties, with α representing the emission's share of output and $1-\alpha$ the effective labor share.

Firms operate under monopolistic competition and disregard the impact of their decisions on aggregate variables in either the product or the input markets. Considering an environmental policy we assume a tax p_e on emissions.[9] Firms take as given the wage rate w and the price of emissions p_e. Firm's optimal demands for labor and emissions are obtained from total production cost minimization subject to Equation (8):

$$\ell_\omega = \left(\frac{1-\alpha}{\alpha b}\frac{p_e}{w}\right)^{\alpha} bq_\omega + a. \tag{9}$$

$$e_\omega = \left(\frac{\alpha b}{1-\alpha}\frac{w}{p_e}\right)^{1-\alpha} q_\omega. \tag{10}$$

[9] In the case of china, as in most countries nowadays, firms are charged for a number of polluting emissions, such as SO2 or waste water.

Firm's optimal emission intensity can thus be expressed as a function of the relative price of inputs, based on Equation (7) and using the optimal demand for emissions (10):

$$\frac{e_\omega}{q_\omega} = (1-\theta_\omega)^{\frac{1-\alpha}{\alpha}} = \left(\frac{\alpha b}{1-\alpha}\frac{w}{p_e}\right)^{1-\alpha}. \tag{11}$$

The optimal emission intensity increases as the wage rises relative to the emission price p_e, making emissions relatively less expensive. The aggregate demand for an intermediate variety, which is taken as given by the monopolistic competitive firms, sums all demands arising from the ordinary and processing good sectors in the two countries:[10]

$$q_\omega = d_{o\omega} + d_{p\omega} + \tau_o^* m_{o\omega}^* + \tau_p^* m_{p\omega}^* = p_\omega^{-\sigma}\left(\frac{D_o}{P_o^{1-\sigma}} + \frac{D_p}{P_p^{1-\sigma}} + \frac{M_o^* \tau_o^{*-\sigma}}{Q_o^{*1-\sigma}} + \frac{M_p^* \tau_p^{*-\sigma}}{Q_p^{*1-\sigma}}\right). \tag{12}$$

The two usual equilibrium conditions in monopolistic competition apply. First, marginal revenue must be equal to marginal cost, leading to the optimal pricing rule of a mark-up charged over the marginal cost of production:

$$p_\omega = \frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{\alpha^\alpha (1-\alpha)^{1-\alpha}} w^{1-\alpha} p_e^\alpha. \tag{13}$$

Second, free-entry on the market generates zero profits for all firms, which results in the following optimal per firm output:

$$q_\omega = (\sigma-1)\frac{\alpha^\alpha (1-\alpha)^{1-\alpha}}{b^{1-\alpha}} a \left(\frac{w}{p_e}\right)^\alpha. \tag{14}$$

[10] If most countries have processing and ordinary production activities, they do not report them separately as in the case of China. However, we find it convenient to maintain this symmetric separation for both countries.

Given that firms in a country have the same technology and face the same environmental policy, all varieties are produced at the same price and in the same quantity in each country: $p_\omega = p$ and $q_\omega = q$ for all $\omega \in [1, n]$.

2.2 Equilibrium conditions

We restrict our attention to intra-industry trade in intermediates, which is at the heart of the distinction between ordinary and processing trade regimes. We treat world prices of final goods p_k as given (small open country assumption) and identical in both countries because of free trade in final goods.

Determination of wages and number of intermediate varieties. The first set of equilibrium conditions is that profits equal zero in the final good industries in both countries, which follows from free-entry under perfect competition in these industries. For final industry $k = \{o, p\}$ in Home:

$$p_k = \frac{C_k}{Y_k} = \frac{1}{\Gamma_k}\left[\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}}\right]^{\gamma_k+\lambda_k}\left(n^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^{\alpha}\right)^{\gamma_k}\left(n^{*\frac{1}{1-\sigma}}\phi_k^{\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\lambda_k}w^{1-\gamma_k-\lambda_k}, \quad (15)$$

where $\phi_k = \tau_k^{1-\sigma} = \tau_k^{*1-\sigma}$ is the degree of trade openness between countries in industry k. The zero profit conditions are characterized by four equations with four unknowns: wages w and w^*, and number of intermediate varieties n and n^*. Wages are a function of trade openness ϕ and final good prices p that incorporate the domestic environmental policy p_e (see Equation 13):

$$w = \left[\frac{\left(\Gamma_p p_p \phi_p^{\frac{\lambda_p}{\sigma-1}}\right)^{\gamma_o+\lambda_o}}{\left(\Gamma_o p_o \phi_o^{\frac{\lambda_o}{\sigma-1}}\right)^{\gamma_p+\lambda_p}}\right]^{\frac{1}{\gamma_o+\lambda_o-\gamma_p-\lambda_p}}, \quad (16)$$

The number of intermediate varieties depends on trade openness and final good prices, as well as directly on the prices of emissions:

$$n = \left[\frac{\left(\Gamma_p p_p \phi_p^{\frac{\lambda_p}{\sigma-1}}\right)^{1-\alpha\gamma_o-\alpha\lambda_o}}{\left(\Gamma_o p_o \phi_o^{\frac{\lambda_o}{\sigma-1}}\right)^{1-\alpha\gamma_p-\alpha\lambda_p}} \left(\frac{\sigma}{\sigma-1} \frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}} p_e^{\alpha} \right)^{\gamma_o+\lambda_o-\gamma_p-\lambda_p} \right]^{\frac{\sigma-1}{\gamma_o+\lambda_o-\gamma_p-\lambda_p}}. \quad (17)$$

The equilibrium expressions are symmetrically equivalent for n^* and w^*.

Determination of final good outputs. The second set of equilibrium conditions corresponds to the conditions of full employment of labor and market clearing for intermediate varieties in each country. These full employment of resources conditions are characterized by four equations in four unknowns: Y_o, Y_p, Y_o^*, Y_p^*. Given the equilibrium wages and the number of varieties (Equations 16 and 17), the production of final goods is a function of the final goods price, trade openness, domestic environmental policy, and labor endowments L and L^*. Equilibrium conditions and analytical expressions for Y_o, Y_p, Y_o^*, Y_p^* are presented in the Appendix section A.1.

Using the equilibrium values, we now work out the environmental impact of trade openness in each final good industry: ordinary and processing.

2.3 Environmental Impact of Trade Openness

We are interested here in ascertaining the effect of trade openness on domestic emission intensity. Pollution is a by-product of the production of intermediates, and we define domestic emission intensity as Θ, i.e., as the ratio of emissions E to GDP. We verify that, given the equilibrium values of both final and intermediate outputs, the sum of value added in the three industries amounts to national income, consisting of revenues from labor (wL) and environmental policy (p_eE). Then, using firm's optimal emission intensity (Equation 11) and the equilibrium values, the emission intensity of the economy is equal to:

$$\Theta = \frac{\alpha\,(\sigma-1)\,a}{p_e}\frac{n}{L+\alpha\,(\sigma-1)\,an}. \tag{18}$$

The model delivers two intuitive and straightforward effects that we can work out before presenting the environmental impact of trade openness. First, domestic emission intensity increases with the number of domestic intermediate firms

$$\frac{d\Theta}{dn} = \frac{\alpha\,(\sigma-1)\,a}{p_e}\frac{L}{\left(L+\alpha\,(\sigma-1)\,an\right)^2} > 0. \tag{19}$$

Second, domestic emission intensity decreases with the tax p_e on emissions

$$\frac{d\Theta}{dp_e} = -\frac{\alpha\,(\sigma-1)\,a}{p_e^2}\frac{n}{L+\alpha\,(\sigma-1)\,an} < 0. \tag{20}$$

Trade openness in industry k, which corresponds to an increase in ϕ_k, has no direct impact on emission intensity (18), but an indirect one through changes on wages w (16) and the number of domestic intermediates n (17). Interestingly, an increase in trade openness in the ordinary and processing industries are found to have opposite effects on wages and the number of domestic intermediates (see Appendix A.2).

Since the value added is relatively higher in the ordinary industry than in the processing (assembly) industry, which implies that $\gamma_o + \lambda_o < \gamma_p + \lambda_p$ (see discussion above on the production parameters), and given Equation 18 we can derive the following effects of trade openness on the environment:

Proposition 1 *(i) Ordinary and processing trade openness have opposite effects on the emission intensity:*

$$\frac{d\Theta}{d\phi_o} = \frac{\Theta}{\phi_o} \frac{L}{L + \alpha (\sigma - 1) an} \frac{\lambda_o (1 - \alpha\gamma_p - \alpha\lambda_p)}{(\gamma_p + \lambda_p - \gamma_o - \lambda_o)} > 0, \tag{21}$$

and

$$\frac{d\Theta}{d\phi_p} = -\frac{\Theta}{\phi_p} \frac{L}{L + \alpha (\sigma - 1) an} \frac{\lambda_p (1 - \alpha\gamma_o - \alpha\lambda_o)}{(\gamma_p + \lambda_p - \gamma_o - \lambda_o)} < 0. \tag{22}$$

(ii) The lower the cost share of imported intermediates in the ordinary industry, λ_o, the lower the trade openness effect of ordinary activities on the emission intensity:

$$\frac{d^2\Theta}{d\phi_o d\lambda_o} = \frac{\Theta}{\phi_o} \frac{L}{L + \alpha (\sigma - 1) an} \frac{(\gamma_p + \lambda_p - \gamma_o)(1 - \alpha\gamma_p - \alpha\lambda_p)}{(\gamma_p + \lambda_p - \gamma_o - \lambda_o)^2} > 0. \tag{23}$$

The main result is that the impact of opening up to trade is deeply dependent on the respective intensity of labor versus domestic and foreign intermediate inputs. This result is the direct consequence of the opposite impact of ordinary and processing trade openness on wages and the number of domestic intermediates (see Appendix A.2). With trade openness in the processing industry both wage rates and the number of domestic intermediates go down. This helps substituting domestic intermediates (which pollute locally) for foreign intermediates and labor in the production process. If processing trade openness generates lower emission intensity, ordinary trade openness by contrast induces higher emission intensity, notably by increasing the share of polluting domestic intermediates. However, the lower the cost share of imported intermediate inputs, λ_o, the lower the detrimental effect of trade liberalization on the environment (see Equation 23). The intuition is that, in this case, trade liberalization will be less relevant.

3 Empirical specification

3.1 Equation to Be Estimated

Our empirical analysis assesses the environmental consequences of trade liberalization in China relying on an IV approach. An open question is whether trade liberalization affects the environment differently regarding processing or ordinary activities. Our theoretical model predicts opposing effects of ordinary and processing trade following trade liberalization. But before exploring this question, we first want to estimate the net effect of overall trade openness. This overall effect is ambiguous in our model and depends on the relative importance of the two different trade regimes. Furthermore, investigating the net effect allows us to place our results into the main literature on the effect of trade openness on pollutant emissions (Antweiler et al., 2001, Cole and Elliott, 2003, Frankel and Rose, 2005 and McAusland and Millimet, 2013). Our benchmark specification is as follows:

$$\ln \text{Pollution}_{ct} = \beta_1 \text{TradeOpen}_{ct} + \beta_2 \ln \text{Income}_{c,t-1} + \beta_3 KE_{ct} + \beta_4 Z_{ct} + \mu_c + \nu_t + \epsilon_{ct}. \quad (24)$$

Our main dependent variable, Pollution_{ct}, is per-capita sulfur emissions (SO_2) for year t and city c. This way of measuring pollution has many advantages. First, SO_2 is one of the main air pollutants in China, and is highly correlated with other airborne pollutants that we do not observe at the city level.[11] Second, our theory focuses on local emissions as a by-product of output. SO_2 is a by-product of goods production and is more localized compared to other pollutants such as CO_2, which is a global externality. The largest sources of SO_2 emissions are from fossil fuel combustion at power plants and other industrial facilities, which are directly linked to the production of goods.[12] Third, we observe variation in SO_2 emissions across industries and cities and also within industries and cities over time, which provides a source of identification. While our benchmark specification uses SO_2 emissions per capita, we check the robustness of our results by using SO_2 per GDP and emissions of soot (black carbon).

Our coefficient of interest is β_1, the effect of trade openness of Chinese city c in year t on local emission intensity. Trade openness is measured as the ratio of city's international trade (exports plus imports) to its GDP. We rely on this measure because it is easy to compute for a large number of cities over the years. We assume that greater trade openness partly results from lower trade costs as stated in the model. Our IV strategy will also rely on instruments for trade openness that capture changes in trade costs. The main prediction of our theoretical model concerns the differential effect of processing and ordinary trade. To uncover the role of trade and production organization on emission intensity, we distinguish trade flows according to the trade regime and construct trade openness separately for each trade regime. Ordinary (processing) trade openness is defined as city's exports plus imports of ordinary (processing) activities over the city's GDP.

[11] Other major air pollutants in China include particulate matter, ozone and nitrogen dioxide. There are however no statistics on their emissions for a panel of cities over a long period of time.

[12] Other measures of local air pollution, such as nitrogen dioxide and particulate matter, are less directly linked to production because they are also produced by diesel engines.

We further include in Equation 24 the logarithm of per capita income, $\text{Income}_{c,t-1}$. This variable is typically used in the empirical literature to capture scale and technique effects (see Cole and Elliott, 2003). These effects go in opposite directions: while pollution grows with economic activity (scale effect at the intensive margin), the demand for environmental quality and adoption of cleaner production technology are expected to rise with income (technique effect) and to reduce pollution. We use lagged income to help mitigating any simultaneity issues. The city-level capital to employment ratio, KE_{ct}, is introduced to capture local factor endowments and a potential composition effect. This composition effect would reflect the change in emissions due to a change in the mix of goods produced, e.g., devoting more resources to producing a polluting good will pollute more. As used in the literature, the squares of per capita income and capital endowment are introduced to allow for non-linear effects.

City fixed effects, μ_c, control for any time-invariant city characteristics and ν_t captures annual shocks that are common to all Chinese cities. Our empirical strategy hence exploits within-city variation over time, and thus addresses the question of the impact of a *change* in trade openness on city pollution.

Finally, Equation (24) includes the usual error term, ϵ_{ct}, and a rich set of city controls, Z_{ct}, which account for some remaining time-varying confounding factors that may be correlated with both the city's environmental and its trade performance. We account for per capita land area, as population density leads to environmental degradation at a given level of per capita income (Frankel and Rose, 2005). We also control for three well-known determinants of both technological progress and trade performance: foreign-capital intensity, human-capital endowments, and technology development areas (see Wang and Wei, 2010). First, foreign capital intensity is proxied by Foreign Direct Investment (FDI) over GDP, reflecting the growing literature suggesting that the large influx of foreign capital into China has resulted in cleaner business practices (Cole et al., 2011; Dean and Lovely, 2010). Next, human-capital endowments are proxied by university-student enrollment. Finally, the development of high- and new-tech sectors is picked up by a dummy for the presence of technology development areas.[13]

Two additional variables attempt to account for emissions related to the production and consumption structures: The employment share in the secondary sector captures the relative size of manufacturing in the economy, while the annual consumption of electricity (in kwh) accounts for energy demand, which is one of the main sources of emissions.

3.2 Addressing Endogeneity

We address the potential endogeneity of trade openness by adopting an instrumental-variable strategy.[14] To capture changes in trade over GDP due to changes in trade costs, we extract exogenous variations from two sources: (1) changes in the proximity of foreign suppliers and (2) variations in from nationally-implemented trade protection of imports and exports. For our aggregate results, presented in Section 5.1, we use the proximity of foreign suppliers as an instrument for trade openness. This variable is derived from a structural gravity estimation following the methodology proposed by Redding and Venables (2004). It is a trade-cost weighted measure of foreign supplier size, which excludes the supply- and demand-side features of Chinese cities. For our main analysis by trade regime, presented in Section

[13] We use the list established by Wang and Wei (2010) of Economic and Technological Development Areas and Hi-Technology Industry Development Areas.

[14] The instruments are presented in greater detail in Section 4.4.

5.2, we add three additional instruments for which we expect different effects on the two different trade regimes. These instruments are based on the exposure of a city to changes in average import tariffs and export taxes. These three policy-induced instruments incorporate information on time-varying tax rates that are decided at the national level, hence avoiding any reverse causality from pollution-intensity between 2003 and 2012 at the local level.

4 Data, Stylized Facts and Instruments

4.1 City-level Pollution Data

Our main dependent variable is the sulfur-dioxide (SO_2) emissions per capita of Chinese cities. SO_2 emissions are taken from the Urban Statistical Yearbook, published by China's State Statistical Bureau. In robustness checks, we also appeal to soot emissions from the same source.[15] We retain all observations for which information on income, pollution and trade is not missing, but exclude 15 cities which are identified as outliers using the hadimvo method (Hadi, 1994). Our final data set consists of a panel of 234 prefecture-level cities for the years 2003 to 2012.[16]

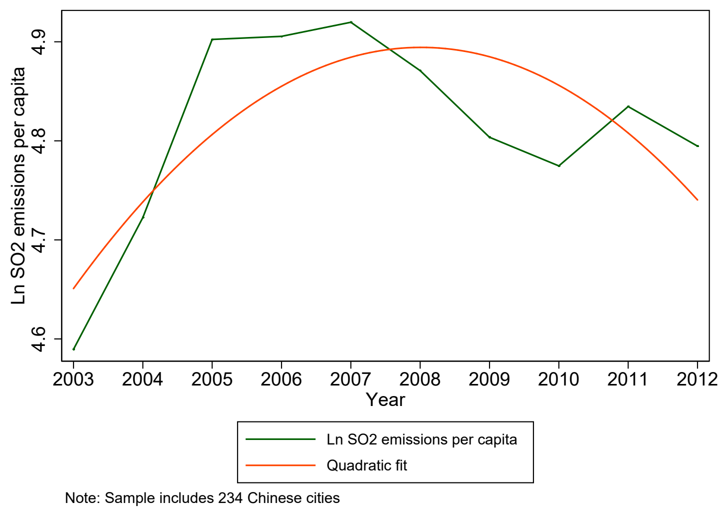
SO_2 emissions per capita increased on average between 2003 and 2007, followed by a downward trend which has continued also after the end of our sample period (Figure 1). The average reduction in SO_2 can partly be explained by national government attempts to reduce pollution by implementing several environmental policies. In our empirical strategy,

[15] The cross-city correlations between SO_2 and soot are between 0.7 and 0.8 for our sample years.

[16] 2003 is the first year in which data on SO_2 emissions is available at the city level. SO2 emissions per population at the city level is available for 285 cities but removing observations with missing data for control variables and instruments, and dropping outliers, leaves us with 234 cities and 2,282 observations, representing close to 50% of China's trade over the sample period.

national environmental policies are captured by year fixed effects.[17] The top panel in Table D-1 reports summary statistics on our different pollution intensity variables and Figure D-1 shows the spatial pattern of SO2 emissions per capita in 2003, the first year for which we have available data for a reasonable amount of cities.

Figure 1: Average sulfur-dioxide emissions in China (2003-2012)



4.2 City-level Trade Data

International trade data by trade regime (ordinary or processing) and city comes from Chinese customs data from 2003 to 2012, which provides bilateral exports and imports at the HS 8-digit product level. For our trade openness variables aggregate yearly exports and imports over all industries and by prefecture-level city. Trade openness for processing and ordinary trade rely only on the trade flows in the respective trade regime. For aggregate trade openness, we sum exports and imports of both types. We rely on the industry dimen-

[17] In 1998, the central government implemented the Two Control Zone policy, which aimed at reducing air pollution in 175 polluting cities. Our city fixed effects take into account whether a city has been assigned to this policy or not.

sion of the data to construct export shares by regime type at the HS 6-digit level for our two instruments based on export taxes. For the instrument based on import tariffs, we construct import shares at the 4-digit level.[18]

The processing sector, which imports inputs to process them in China and re-exports the final products, accounts for 41% of China's trade between 2002 and 2012.[19] Overall, over the sample period, exports and imports for both trade regimes have increased in all years, with an exception during the financial crisis in 2009. There is however a relative decline in total processing trade with respect to ordinary over the time period, which is mainly driven by a relative decrease in processing imports after 2006. Processing exports and ordinary imports have grown at similar rates as ordinary exports. As a consequence in our sample, the average trade openness for processing trade is 4.60 in 2002 and 3.4 in 2012, while for ordinary activities, trade openness is on average 10.7 in 2002 an 10.6 in 2012. Summary statistics on the different trade openness measures are reported in the second panel in Table D-1.

4.3 City-level Macro Indicators

City-level variables such as GDP, population, electricity consumption, employment share in manufacturing, FDI, university student enrollment as a measure of human capital[20] come from China Data Online, provided by the University of Michigan. The capital abundance of cities (K) corresponds to the physical capital stock, calculated according to the method

[18]To account for the changes in the HS classification in 2002, 2007 and 2012, we aggregate the data to the HS 6-digit level (1996 revision). The correspondence tables from UNCTAD can be found at http://unstats.un.org/unsd/trade/conversions/HS Correlation and Conversion tables.htm.

[19]Roughly 84% of this assembling-trade over the period comes from foreign-invested enterprises.

[20]Data on school completion are unfortunately not available at the city level.

used by Mankiw et al. (1992) and described in the Appendix (B).

4.4 Instruments for Trade Openness

To capture the link between trade and pollution that is driven by changes in trade costs, as it is modeled in Section 2, and to address the endogeneity of trade with respect to pollution, we rely on an instrumental variable strategy. Our instruments focus on the part of city trade performance that is driven by changes in trade costs. We use the proximity to foreign suppliers, which is expected to have similar effects on processing and ordinary trade, and China's trade protection, which varies across regime types. For our aggregate results, we instrument the city's overall trade openness with the local foreign supply access. For our analysis distinguishing between the two different types of trade, we add three additional instruments based on trade protection.

Foreign supply access

The underlying idea of the foreign supply access variable (FSA) is that a location's import performance depends on its accessibility to all potential trading partners. Thus, locations closer to large supplier markets have greater supply access due to lower trade costs. This gives them a competitive advantage in importing from these markets. We thus expect cities with greater FSA to import more from abroad, independently of their pollution emissions.

In order to compute the FSA variable, we exploit information from the estimation of bilateral trade as in Redding and Venables (2004). We use bilateral trade between Chinese cities and 179 foreign countries as well as between countries.[21] All of the estimated coefficients

[21] International trade data of foreign countries come from the IMF Direction of Trade Statistics.

are allowed to vary over time. We thus estimate the following trade equation, which enables us to construct yearly city-level FSA measures:

$$\ln EX_{ijt} = \underbrace{\delta_t \ln \text{Distance}_{ij} + \eta_t \text{Border}_{ij} + \vartheta_t WTO_{ijt}}_{\text{Bilateral trade costs}} + FM_{jt} + FX_{it} + \epsilon_{ijt}, \qquad (25)$$

where, for a given year t, EX_{ij} denotes bilateral exports between trading partners i and j, explained by bilateral trade costs as well as exporter and importer fixed effects. Trade costs between i and j can be specified using different variables. We consider bilateral distance (Distance_{ij}), whether partners share a common border (Border_{ij}), and whether the two are members of the WTO or its predecessor GATT (WTO_{ijt}). These variables are obtained from CEPII. Distances between Chinese cities and foreign countries are constructed using latitudes and longitudes, as follows: since most of China's trade is shipped by boat, we first calculate the geodesic distance of each Chinese city to one of the closest 17 largest Chinese harbors[22] and then add the geodesic distance from the harbor to the foreign destinations.

Importer-by-year fixed effects (FM_{jt}) capture all the considerations that make destination j attractive, such as its total expenditure on imported goods and the prevailing price index. The higher FM_{jt}, the greater its market capacity and thus the greater its demand for imported goods from each country of origin. Exporter fixed effects (FX_{it}) pick up whatever makes exporter i competitive in a given year, including the number of firms, their total output and their price competitiveness. The higher FX_{it}, the greater the region i's supply capacity and thus the more it exports to each destination j. For each year, we sum for each city c the predicted supply capacity of all destinations j, FX_{it}, weighted by the estimates of

[22] The ports used are Beibuwan, Dalian, Fuzhou, Guangzhou, Lianyungang, Qingdao, Qinhuangdao, Rizhao, Shanghai, Shenzhen, Suzhou, Tangshan, Tianjin, Xiamen, Yingkou, Zhanjiang and Zhoushan.

the corresponding bilateral trade costs. As supply capacities and trade costs vary by year, we can construct a time-varying foreign supply access indicator for each city (FSA_{ct}):

$$\text{FSA}_{ct} = \sum_{i \in R} \exp\left(\widehat{\delta}_t \ln \text{Distance}_{ic} + \widehat{\eta}_t \text{Border}_{ic} + \widehat{\vartheta}_t WTO_{ict} + \widehat{FX}_{it}\right), \tag{26}$$

where R denotes the set of foreign countries. This structurally constructed FSA corresponds to a trade-cost weighted measure of the city's foreign suppliers' size. It does not reflect supply-side features that are specific to a Chinese city, such as local comparative advantages due to the availability of specific resources, any particular production technology or greater local productivity. It also does not incorporate local demand-side features such as income per capita, which could potentially affect the city's SO_2 emissions.[23]

Trade protection

For our analysis that separates processing from ordinary trade, we further rely on three additional instruments, which can account for differences in these two types of trade in a given year. These instruments rely on national-level information on trade protection (import tariffs and export taxes), hence avoiding any reverse causality from pollution-intensity to trade at the local level.

The first instrument, *Weighted import tariffs*, is calculated from 2002 to 2012 as the

[23]It should be noted that access to foreign suppliers is correlated with access to foreign consumer markets, which are also key drivers of local exports. In unreported robustness checks, we also construct an indicator of foreign market access (FMA_{ct}) in the same way as our proxy of foreign supply access, but using instead of the predicted supply capacities (FX_{it}) the predicted market capacities (FM_{jt}). The correlation rate between the FMA and FSA variables is 0.73 even after accounting for city and year fixed effects. We therefore refrain from using the two variables simultaneously as instruments and show in the following pages only the results obtained with the FSA, because this variable is also better able to capture the import dimension, and in particular to capture the processing trade activities. Results on aggregate trade openness relying on FMA instead of FSA as an instrument are however highly similar.

weighted average of product-level nominal tariff applied to imports into China, using the product's share at the highly disaggregated HS 6-digit level (1996 revision) in 2000 city imports as the weight. Annual data on MFN tariffs at the HS6-level come from the World Integrated Trade Solution. Higher import tariffs are expected to hit exclusively ordinary imports as processing activities are exempted from these tariffs. However rising import tariffs may provide processing activities with a relative advantage insofar as they now face less competition from ordinary activities for their use of the best inputs, particularly foreign inputs. on from the ordinary firms in the demand for the best foreign inputs. We interact the import tariff variable with a dummy for coastal provinces, where most of the import intensive activities are located. This variable therefore takes the value of zero for cities not located in a coastal province.

The second two trade protection instruments are based on export taxation, which is common in China. A growing literature on the Chinese Value-Added Tax (VAT) export rebate system (Chandra and Long, 2012; Evenett and Jing, 2012; Gourdon et al., 2015) highlights that export quantities are negatively affected by the ad-valorem tax on exports that is imposed when goods receive a VAT refund rate that is lower than the applicable VAT rate. Over the 2002-2012 period, only 13% of the products in China received rebates compensating for VAT. Incomplete rebates, which are thus equivalent to export taxation (Feldstein and Krugman, 1990), are hence the rule in China. However, in contrast to ordinary trade and processing traded with imported materials, processing trade with supplied materials is not entitled to any refund on domestic VAT or asked to pay VAT on their shipments. This is, because as ownership of the supplied material stays with the foreign party, no transaction takes place and therefore no VAT is charged. As a consequence, processing exports, which includes a high share of processing trade with supplied materials, are not expected to react (much) to changes in export VAT rebates (Gourdon et al., 2015).

Our measure of the export tax is given by ln(1 + VAT-rate - VAT export rebate), which gives us the value 1 if the tax is zero. This ensures that when aggregating the different products within the same city, all products are included and not dropped due to a full rebate. VAT rates and VAT rebate rates at the tariff-line level (HS 8-digit or more disaggregated levels) are taken from the Etax yearbooks of Chinese Customs.[24] We calculate the weighted average of the product-level share of non-refunded VAT, using the product's share in 2000 city exports as the weight. We construct these variables separately for ordinary and processing trade for each city. For ordinary trade, we rely uniquely on the export basket of ordinary trade in 2000 and for processing trade, we use only exports from 2000 that are declared as processing trade.

To further ensure the reliability of our IV strategy, both taxation-related instruments are lagged one year with respect to the trade openness indicator. We expect ordinary trade to react strongly to its own export taxation. However, an increase in export taxes might also lead firms to switch away from ordinary to processing trade with supplied materials to avoid these higher costs. The maps in Figures D-2 to D-4 show the evolution of these three instruments between 2002 and 2012 for each city.

[24] To account for the changes in the HS classification in 2002, 2007 and 2012, we aggregate the data to the HS 6-digit level (1996 revision) using the yearly average of these rates. We use the simple average of all tariff lines within a HS6 product and all sub-periods within the year.

5 Results

5.1 Baseline results of aggregate trade openness on pollution

In this section, we first report results on pollution using city's aggregate trade openness, without distinguishing between processing and ordinary trade. Even though the theoretical model has clear predictions on the emissions by each type of trade openness, the net effect is ambiguous and depends on which trade regime dominates. Also, in practice there might be other factors, such as environmental policies that might apply particularly to polluting exporters, and may lead to an overall beneficial effect of trade on the environment, but which is independent of the type of trade. Finally, studying aggregate trade openness allows us to better place our results into the literature.

Table 1 therefore shows the estimates for Equation 24 on the city's aggregate trade openness, instrumenting trade openness with city's access to foreign suppliers. All columns include city and year fixed effects. Column 1 includes as controls city per capita land area, inflows of foreign investment, university-student enrollment and a dummy denoting the presence of a technology development area. Column 2 further adds the employment share in the secondary sector and total electricity consumption to account for emission sources related to production and consumption structures. All these control variables attract coefficients with the expected signs when statistically significant. The proxies for education and technology-promoting policy enter with significant negative signs, confirming that pollution is lower in locations with greater levels of skill and technology. Moreover, the estimates are negative and significant for education and technology-supporting policy, and positive and significant for the employment share in manufacturing and electricity consumption. The specification of column 2 constitutes our benchmark in the remaining tables.

The estimated effect of trade openness on SO_2 per capita emissions remains constant over the different specifications and is always negative and significant, suggesting that overall greater international trade openness leads to less local pollution. Following our model, this negative effect can arise if the negative effect of processing trade dominating ordinary trade.

The first stages of the first two columns of Table 1 appear in Column 1 and 2 of Table D-3. These first-stage results show that, as expected, greater proximity to foreign suppliers boosts the trade performance of Chinese cities. The partial explanatory power of the excluded instrument is about 3%. Additional test statistics regarding our instruments appear at the bottom of Table 1. These show that our instruments pass standard validity assessments.[25] The Angrist-Pischke first-stage Chi-squared statistics rejects the null of under-identification (Angrist and Pischke, 2009). This indicates that we do not suffer from a weak instrument. As we have only one instrument here, we cannot test for its exogeneity.

It is worth comparing the IV estimates of the trade openness in Table 1 with the OLS results, which are presented in the first two columns in Table D-2). OLS estimates report an insignificant effect of trade openness on pollution and thus seem to be upward-biased. This either reflects measurement error, which typically induces a bias toward zero, or the omission of variables that are correlated with both trade openness and emissions, such as the availability of natural resources or large and competitive local supply capacity.

The empirical specification in column 3 of Table 1 follows the work of Antweiler et al. (2001), where the squares of per capita income and capital endowment are introduced to allow

[25] The first stage F-statistics on the excluded instruments easily matches the informal threshold of 10 suggested by Staiger and Stock (1997) to assess instrument validity.

Table 1: The impact of trade openness on SO_2 emissions

Dependent variable	Ln SO2 emissions				
	per capita				over GDP
	(1)	(2)	(3)	(4)	(5)
Trade openness ([X+M]/GDP)	-0.056[a]	-0.057[a]	-0.059[a]		-0.061[a]
	(0.015)	(0.014)	(0.014)		(0.015)
Domestic VA of Trade openness				-0.115[a]	
				(0.026)	
Lagged ln GDP per capita	-0.203	-0.257[c]	0.890	-0.399[b]	-1.045[a]
	(0.139)	(0.142)	(1.247)	(0.166)	(0.151)
Capital abundance (K/E)	-0.590	-0.423	11.854	-0.254	-0.429
	(0.834)	(0.828)	(15.685)	(0.817)	(0.854)
ln Land area per capita	-0.001	0.001	-0.001	0.001	-0.000
	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)
FDI over GDP	0.002	0.024	-0.004	0.024	0.018
	(0.093)	(0.092)	(0.093)	(0.095)	(0.097)
Share of Univ student in population	-1.240[a]	-1.128[a]	-0.659[c]	-1.590[a]	-1.242[a]
	(0.349)	(0.339)	(0.352)	(0.427)	(0.350)
Technology development area	-0.230	-0.336[c]	-0.428[b]	-0.471[c]	-0.457[b]
	(0.180)	(0.193)	(0.192)	(0.243)	(0.203)
Employment share in secondary sector		1.420[a]	1.439[a]	1.343[a]	1.483[a]
		(0.474)	(0.487)	(0.449)	(0.490)
ln Electricity consumption		0.197[a]	0.183[a]	0.208[a]	0.201[a]
		(0.052)	(0.050)	(0.054)	(0.053)
Lagged (ln GDP per capita)^2			-0.051		
			(0.069)		
$(K/E)^2$			28.732[b]		
			(12.242)		
K/E $\times$ Lagged ln GDP per capita			-1.810		
			(1.734)		
City and year fixed effects	Yes	Yes	Yes	Yes	Yes
No. of observations	2282	2282	2282	2282	2282
No. of cities	234	234	234	234	234
Partial R^2 of excluded instruments	0.032	0.033	0.031	0.030	0.033
Underidentification test	26.22	27.18	27.52	24.04	27.18
Weak identification test	43.91	46.86	47.26	44.78	46.86

Notes: Heteroskedasticity-robust standard errors appear in parentheses. [a], [b] and [c] indicate significance at the 1%, 5% and 10% confidence levels. Column 2 constitutes our benchmark in the remaining tables. The underidentification test reports the Kleibergen-Paap rk LM-statistic. The p-values (Chi-sq(2)) are all below 0.01 (not reported), suggesting that underidentification is rejected. The weak identification test is based on the Kleibergen-Paap Wald rk F-statistic. To assess instrument validity, we compare this to the critical value of the Staiger and Stock (2005) F-statistic for one endogenous regressors and one instrument, which is 16.38 for 10% maximal IV relative bias. Domestic value-added in trade is calculated using the HS4-level ratios of domestic value-added calculated from firm-level data for 2006.

for non-linear effects. The environmental Kuznets curve literature does indeed propose a hump-shaped relationship between per capita income and pollution (Grossman and Krueger, 1993; Selden and Song, 1994). The interaction $KE \times \ln \text{Income}_{c,t-1}$ captures any effect of per capita income on pollution that depends on relative capital endowments, and vice versa. These additional controls fail to enter significantly except the estimated coefficient on $(\text{K/E})^2$, which is significant at the 10% level.

How economically meaningful is the trade openness estimate?

The results in the first three columns of Table 1 show that the estimate of the trade openness is reasonably insensitive to a number of different controls. This estimate suggests that a 1 percentage point increase in trade openness reduces emission intensity by about 6%. Over our sample period (2003-2012) the average annual change in city-level trade openness was 2.1 percentage point, so that emission intensity fell by 12% annually as a result of China's greater outward orientation. This value does however mask an important spatial heterogeneity. Comparing the 75^{th} and 25^{th} percentile cities in terms of the annual change in trade openness (-4.8 and + 5.3 percentage points, respectively) the point estimate implies that pollution emissions per capita rose by 30% per annum for the former but fell by 27% p.a. for the latter.

Robustness checks on aggregate trade openness

In the fourth column of Table 1 we rely on a trade openness measure that uses domestic value-added (DVA) in trade instead of the total value of trade. This allows us to ensure that our results do not simply reflect any overstatement of Chinese trade openness related to the well-known "double-counting" problem when processing trade is pervasive (Johnson and Noguera, 2012; Koopman et al., 2012). Indeed, as official trade statistics are measured in gross terms, they "double count" the value of intermediate goods that cross the Chinese border. Thus, our international trade openness ratios are potentially distorted measures of the cities' internationalization due to the high share of imported intermediates. To avoid double counting, we recompute the trade openness measures, TradeOpen_{ct}, as the ratio of international DVA exports plus imports to GDP of Chinese city c in year t. We compute DVA exports at the city level using firm-level declarations of imports and exports in 2006.[26] First, we remove firms' imports (at the HS4 level) from firms' exports to get rid of what is potentially double counted. Then, we sum over firms and HS4 sectors the DVA values for each city-year pair.

The negative association between trade openness and emissions remains when the former is measured in terms of the value-added content of trade. The point estimate is slightly higher, but not statistically different from that in our benchmark. The last column of Table 1 further checks that our results hold when pollution intensity is measured dividing SO_2 emissions by GDP instead of population. We find that the negative and significant effect of trade on emissions is insensitive to the scaling of the pollution measure.

Table 2 goes further in sensitivity testing and considers alternative pollution measures. Column 1 considers soot emissions per capita while column 2 looks at soot emissions per unit of GDP.[27] Our results hold also for these alternative emissions measures.

[26] This is the latest year for which we have the firm-level customs data and the mid-period of our estimation sample, 2003-2012.

[27] Soot is the main pollutant from burning coal. Poor production methods and widespread use of coal make China the world's largest source of black carbon. This results mainly from coke production, brick making, diesel fuel and household coal. Some of its particles (notably the tiniest ones - qualifying as PM2.5) are the deadliest form of air pollution due to their ability to penetrate unfiltered deep into the lungs and

The last three columns of Table 2 run sensitivity tests in terms of city heterogeneity. We check that our results hold after excluding some particular geographic zones. As emphasized in the literature on Chinese export performance (Amiti and Freund, 2010; Wang and Wei, 2010), a number of Chinese cities are clearly different from the others in terms of location and policy particularities, which have made them richer, faster-growing, more open, and more likely to host firms with rapid export growth.

Table 2: The impact of trade openness on pollution: alternative measures

Dependent variable	Ln Soot emissions		Ln SO2 emissions per capita		
	per capita	over GDP	No municipalities	No West	Only Coast
	(1)	(2)	(3)	(4)	(5)
Trade openness ([X+M]/GDP)	-0.065^a	-0.069^a	-0.057^a	-0.060^a	-0.063^a
	(0.016)	(0.017)	(0.014)	(0.014)	(0.015)
Time-varying city controls	Yes	Yes	Yes	Yes	Yes
City and year fixed effects	Yes	Yes	Yes	Yes	Yes
No. of observations	2281	2281	2252	1862	897
No. of cities	234	234	231	190	92
Partial R^2 of excluded instruments	0.034	0.034	0.036	0.041	0.049
Underidentification test	27.56	27.56	26.78	29.41	27.13
Weak identification test	49.04	49.04	46.65	51.13	41.43

Notes: Heteroskedasticity-robust standard errors appear in parentheses. ^{a}, ^{b} and ^{c} indicate significance at the 1%, 5% and 10% confidence levels. The underidentification test reports the Kleibergen-Paap rk LM-statistic. The p-values (Chi-sq(2)) are all below 0.01 (not reported), suggesting that underidentification is rejected. The weak identification test is based on the Kleibergen-Paap Wald rk F-statistic. To assess instrument validity, we compare this to the critical value of the Staiger and Stock (2005) F-statistic for one endogenous regressors and one instrument, which is 16.38 for 10% maximal IV relative bias.

Column 1 excludes the four cities with province status (Beijing, Tianjin, Shanghai, and Chongqing), which stand out by their greater political autonomy and smaller surface area.[28] We also tackle China's interior–coast divide. Column 2 excludes cities in the Western provinces to check that the results are not driven by observations from these landlocked

bloodstream, causing permanent DNA mutations, heart attacks, and premature death (World Bank, 2007).

[28]China is divided into four municipalities (Beijing, Tianjin, Shanghai and Chongqing) and 27 provinces which are further divided into prefectures.

and mountainous areas, which are mostly populated by ethnic minorities.[29] In column 3, we restrict our sample to coastal locations, which account for around 90% of the country's trade. Interior locations are considered to be significantly different from the rest of the country; their economies are more inward-oriented and have had limited success in attracting foreign investment. Despite the much smaller number of observations the coefficient on trade remains negative and significant, so the pollution repercussions of trade are also found in these areas that are responsible for the bulk of trade and growth in China.[30]

5.2 Heterogeneous effects on pollution: processing versus ordinary

In this section, we present our estimates of the main prediction of the theoretical model developed in Section 2. The model predicts a pro-environmental effect of trade openness for processing activities and an anti-environmental effect for ordinary activities. We first present the results and then discuss the findings with respect to the model predictions and the literature.

The first two columns of Table 3 show the estimates for Equation 24, distinguishing trade openness by trade regime. We rely again on an IV approach to deal with the endogenity of the two trade openness variables. We use here all four instruments described in Section 4.4: the foreign supply access which captures very well both processing and ordinary trade, the weighted export tax, separately for ordinary and processing trade, and the interaction of the weighted import tariffs and the coast dummy.

These instruments are chosen to explain the two dimensions of trade openness (exports

[29] The Western part of China includes Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang provinces.

[30] In unreported results (available upon request), we also check that our results continue to hold when the regressions are re-estimated excluding one province at a time.

versus imports) as well as the differences in trade costs between the two regimes (ordinary versus processing). This helps maximize the explanatory power of the first-stage equation and avoid issues relating to weak instruments. The rationale for the interaction of the import tariffs with the coast dummy relates to the concentration of processing trade activities in the coastal region. We thus do not impose the same relationship between trade openness and its exogenous determinants across the Chinese coast-interior divide.

The various tests of instrument weakness appear at the foot of Table 3. The overidentification Hansen J-statistic is also shown, which evaluates instrument exogeneity. None of these tests reject instrument validity. The first stage of the estimations of Column 1 and 2 of Table 3 appear in Column 3 and 4 in Table D-4. First-stage results suggest that greater proximity to foreign suppliers increases the trade performance of all firms, but the coefficient is much higher for processing firms. An increase in the weighted average tax on exports or imports tariffs is detrimental to ordinary trade only, which is consistent with expectations. Processing trade is rather benefiting form an increase in import tariffs, as processing imports are exempted from tariffs.

Column 1 of Table 3 shows a negative effect of trade on SO_2 pollution for both regimes but only the processing estimate is statistically different from zero. The magnitude of the trade estimate on processing trade is much larger than of its ordinary counterpart (-0.07 versus -0.01) and the difference is statistically significant, as is indicated by the t-test reported at the bottom of the table. Further, we note that the coefficient of processing trade openness is slightly larger than our estimate of the aggregate trade openness baseline (-0.06 in Column 3 of Table 1). This holds also after the inclusion of our additional controls (Column 2). This suggests that our IV approach has been successful in identifying an exogenous source

Table 3: The heterogeneous effect of trade openness on SO_2 emissions by type of trade

Dependent variable	Ln SO2 emissions			
	per capita			over GDP
	(1)	(2)	(3)	(4)
Trade openness (processing trade)	-0.076^a	-0.074^a		-0.081^a
	(0.023)	(0.022)		(0.023)
Trade openness (ordinary trade)	-0.014	-0.021		-0.019
	(0.013)	(0.014)		(0.014)
Domestic VA of Trade openness, PCS			-0.156^a	
			(0.045)	
Domestic VA of Trade openness, ODT			-0.034	
			(0.030)	
Lagged ln GDP per capita	-0.083	-0.142	-0.071	-0.910^a
	(0.124)	(0.122)	(0.184)	(0.127)
Capital abundance (K/E)	-0.836	-0.628	-0.964	-0.682
	(0.689)	(0.711)	(0.779)	(0.723)
ln Land area per capita		-0.001	-0.001	-0.003
		(0.002)	(0.003)	(0.003)
FDI over GDP		0.076	0.058	0.080
		(0.092)	(0.099)	(0.097)
Share of Univ student in population		-0.726^b	-0.945^b	-0.777^b
		(0.302)	(0.380)	(0.314)
Technology development area		-0.400^c	-0.535^b	-0.534^b
		(0.219)	(0.260)	(0.230)
Employment share in secondary sector		0.969^a	0.898^b	0.983^a
		(0.358)	(0.360)	(0.365)
ln Electricity consumption		0.166^a	0.186^a	0.167^a
		(0.046)	(0.051)	(0.046)
City and year fixed effects	Yes	Yes	Yes	Yes
No. of observations	2282	2282	2282	2282
No. of cities	234	234	234	234
Partial R^2 of excluded instruments	0.049	0.046	0.028	0.046
Underidentification test	61.09	55.82	27.41	55.82
Weak identification test	14.86	13.36	7.76	13.36
Hansen (p-value)	0.51	0.38	0.30	0.47
T-test	0.03	0.06	0.05	0.03

Notes: Heteroskedasticity-robust standard errors appear in parentheses. ^{a}, ^{b} and ^{c} indicate significance at the 1%, 5% and 10% confidence levels. The underidentification test reports the Kleibergen-Paap rk LM-statistic. The p-values (Chi-sq(2)) are all below 0.01 (not reported), suggesting that underidentification is rejected. The weak identification test is based on the Kleibergen-Paap Wald rk F-statistic. The critical value of the Staiger and Stock (2005) F-statistic to assess instrument validity for two endogenous regressors and four instruments is 7.56 for 10% maximal IV relative bias. We report the Chi-sq(2) p-value of the Hansen J-statistic to test for overidentification of all instruments. A Chi-sq(2) p-value above 0.10 suggests that the model is overidentified and the instruments are exogenous. The T-test shows the p-value which tests for equality of the coefficients on the two trade openness variables. Domestic value-added in trade is calculated using the HS4-level ratios of domestic value-added calculated from firm-level data for 2006. ODT and PCS stand for ordinary and processing, respectively.

of trade openness that is independent of FDI and other traditionally-proposed proxies of technological progress, which are often thought to be correlated with environmental or trade performance.[31]

Sensitivity analysis to the double-counting issue

Column 3 of Table 3 checks that our results do not simply come from processing exports being a biased measure of a location's internationalization due to the high share of imported intermediates.

We recalculate our trade openness measures using the domestic value-added content of imports and exports instead of the total value of trade to avoid the "double counting" issue.[32] Results confirm that trade tends to reduce emissions. Again, this effect is larger for processing trade: there seems to be no substantial benefits from environmental gains from ordinary trade activities even though these are currently the main drivers of China's export and import growth.

Sensitivity analysis to city heterogeneity

As for the aggregate results in Table 2, we show in Table 4 some sensitivity checks with respect to the dependent variable and the sample, to ensure that our results do not depend on particular locations or outliers. In the first two columns we consider again soot emissions per capita and soot over GDP as alternative pollution variable. Difference between processing and ordinary trade is even bigger here with ordinary trade having a positive (but not

[31] In unreported results, which are available upon request, we check that all our results hold when we further control for the share of polluting sectors in imports and exports separately. Polluting sectors (at the 2-digit ISIC level) are defined as those for which the ratio of SO_2 emissions over output is above the median across sectors.

[32] The domestic value-added in trade is computed using firm-level data as in section 5.1).

significant) sign. The remaining columns exclude again different location without changing the main results. However, as the number of observations decreases, the F-stat decreases and the results should be taken with caution for the sample using only coastal provinces.

Table 4: Heterogeneous effects by type of trade: Sample checks

Dependent variable	Ln Soot emissions		Ln SO2 emissions per capita		
	per capita	over GDP	No munici.	No West	Only coast
	(1)	(2)	(3)	(4)	(5)
Trade openness (processing trade)	-0.102^a	-0.109^a	-0.078^a	-0.077^a	-0.101^a
	(0.026)	(0.027)	(0.023)	(0.022)	(0.035)
Trade openness (ordinary trade)	0.020	0.022	-0.016	-0.021	-0.003
	(0.020)	(0.021)	(0.014)	(0.018)	(0.036)
Time-varying city controls	Yes	Yes	Yes	Yes	Yes
City and year fixed effects	Yes	Yes	Yes	Yes	Yes
No. of observations	2281	2281	2252	1862	897
No. of cities	234	234	231	190	92
Partial R^2 of excluded instruments	0.049	0.049	0.049	0.050	0.031
Underidentification test	56.23	56.23	54.11	38.69	8.47
Weak identification test	13.46	13.46	12.97	8.69	2.28
Hansen (p-value)	0.19	0.25	0.75	0.13	0.84
T-test	0.00	0.00	0.04	0.06	0.13

Notes: Heteroskedasticity-robust standard errors appear in parentheses. ^{a}, ^{b} and ^{c} indicate significance at the 1%, 5% and 10% confidence levels. The underidentification test reports the Kleibergen-Paap rk LM-statistic. The p-values (Chi-sq(2)) are all below 0.05 (not reported), suggesting that underidentification is rejected. The weak identification test is based on the Kleibergen-Paap Wald rk F-statistic. The critical value of the Staiger and Stock (2005) F-statistic to assess instrument validity for two endogenous regressors and four instruments is 7.56 for 10% maximal IV relative bias. We report the Chi-sq(2) p-value of the Hansen J-statistic to test for overidentification of all instruments. A Chi-sq(2) p-value above 0.10 suggests that the model is overidentified and the instruments are exogenous. The T-test shows the p-value which tests for equality of the coefficients on the two trade openness variables.

Discussion

Our estimations reveal a beneficial effect of greater trade openness on pollution that is mostly attributable to processing trade. This result is consistent with our theoretical predictions on the local environment, which relies in particular on the substitution of domestic intermediates by foreign intermediates. This local pro-environmental effect does not necessarily imply an anti-environmental effect abroad. The model abstracts from the technological differences between countries. However, we can reasonably assume that some Chinese trading partners, particularly developed countries, use cleaner technologies for the production of intermediate goods.

A particularity of processing trade is its geographical orientation. Close to 92% of processing trade is directed to or emanates from developed countries in the period under consideration, compared to 77% for ordinary trade.[33] Sharper environmental concerns and stricter pollution regulations in developed countries may lead to less harmful environmental practices for processing activities. In unreported results (available upon request) we investigate this channel by separating developed and developing partner countries. The relationship between trade openness and SO_2 emissions per capita is negative and significant for trade with developed countries while no such pattern pertains for trade with developing countries. The consistent message in our results is then that the environmental benefits from increased trade orientation identified in Section 5.1 mostly come from processing trade. The "pro-environmental" effect of processing trade suggests that the ongoing rebalancing process in which China is trying to increase the contribution of domestic consumption and reduce its reliance on processing activities may be detrimental for the environment.

6 Conclusion

We use recent detailed panel data on trade and pollution emissions covering 234 Chinese cities from 2003 to 2012 to assess the environmental consequences of China's integration into

[33]Developed countries are identified as those with a GNP per capita over 10,000 US Dollars (obtained from the World Bank indicators).

the world economy. We explore the differential effects of processing versus ordinary trade on pollution at the city level. Our theory highlights a differential environmental impact of processing versus ordinary trade, which is supported by the data. We take specific account of the endogeneity of trade and find that processing trade tends to reduce local SO_2 emissions. This is not the case for ordinary activities even though these today represent the main drivers of China's export and import growth. This result suggests some caution regarding pollution prospects in the context of the declining role of processing trade.

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A Theoretical Appendix

A.1 Equilibrium conditions and final outputs

Full labor employment conditions:

$$\begin{aligned}
L &= n\ell + \ell_o + \ell_p \\
&= \left[(\sigma-1)(1-\alpha)+1\right] an \\
&+ \frac{(1-\gamma_o-\lambda_o)\,Y_O}{\Gamma_o}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\,\alpha^{\alpha}}\right)^{\gamma_o+\lambda_o}\left(n^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^{\alpha}\right)^{\gamma_o}\left(n^{*\frac{1}{1-\sigma}}\phi_o^{\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\lambda_o}w^{-\gamma_o-\lambda_o} \qquad (27)\\
&+ \frac{(1-\gamma_p-\lambda_p)\,Y_p}{\Gamma_p}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\,\alpha^{\alpha}}\right)^{\gamma_p+\lambda_p}\left(n^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^{\alpha}\right)^{\gamma_p}\left(n^{*\frac{1}{1-\sigma}}\phi_p^{\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\lambda_p}w^{-\gamma_p-\lambda_p},
\end{aligned}$$

and

$$
\begin{aligned}
L^* &= n^*\ell^* + \ell_o^* + \ell_p^* \\
&= [(\sigma-1)(1-\alpha)+1]\,an^* \\
&+ \frac{(1-\gamma_o-\lambda_o)\,Y_O^*}{\Gamma_o}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_o+\lambda_o}\left(n^{*\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\gamma_o}\left(n^{\frac{1}{1-\sigma}}\phi_o^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\lambda_o}w^{*-\gamma_o-\lambda_o} \\
&+ \frac{(1-\gamma_p-\lambda_p)\,Y_p^*}{\Gamma_p}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_p+\lambda_p}\left(n^{*\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\gamma_p}\left(n^{\frac{1}{1-\sigma}}\phi_p^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\lambda_p}w^{*-\gamma_p-\lambda_p}.
\end{aligned}
\tag{28}
$$

Market clearing conditions for varieties of the intermediate product:

$$
\begin{aligned}
\sigma awn =& \frac{\gamma_o Y_o}{\Gamma_o}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_o+\lambda_o}\left(n^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\gamma_o}\left(n^{*\frac{1}{1-\sigma}}\phi_o^{\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\lambda_o}w^{1-\gamma_o-\lambda_o} \\
&+ \frac{\gamma_p Y_p}{\Gamma_p}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_p+\lambda_p}\left(n^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\gamma_p}\left(n^{*\frac{1}{1-\sigma}}\phi_p^{\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\lambda_p}w^{1-\gamma_p-\lambda_p} \\
&+ \frac{\lambda_o Y_o^*}{\Gamma_o}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_o+\lambda_o}\left(n^{*\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\gamma_o}\left(n^{\frac{1}{1-\sigma}}\phi_o^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\lambda_o}w^{*1-\gamma_o-\lambda_o} \\
&+ \frac{\lambda_p Y_p^*}{\Gamma_p}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_p+\lambda_p}\left(n^{*\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\gamma_p}\left(n^{\frac{1}{1-\sigma}}\phi_p^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\lambda_p}w^{*1-\gamma_p-\lambda_p},
\end{aligned}
\tag{29}
$$

and

$$
\begin{aligned}
\sigma aw^*n^* =& \frac{\gamma_o Y_o^*}{\Gamma_o}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_o+\lambda_o}\left(n^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\gamma_o}\left(n^{*\frac{1}{1-\sigma}}\phi_o^{\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\lambda_o}w^{1-\gamma_o-\lambda_o} \\
&+ \frac{\gamma_p Y_p^*}{\Gamma_p}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_p+\lambda_p}\left(n^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\gamma_p}\left(n^{*\frac{1}{1-\sigma}}\phi_p^{\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\lambda_p}w^{1-\gamma_p-\lambda_p} \\
&+ \frac{\lambda_o Y_o}{\Gamma_o}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_o+\lambda_o}\left(n^{*\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\gamma_o}\left(n^{\frac{1}{1-\sigma}}\phi_o^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\lambda_o}w^{*1-\gamma_o-\lambda_o} \\
&+ \frac{\lambda_p Y_p}{\Gamma_p}\left(\frac{\sigma}{\sigma-1}\frac{b^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha}\right)^{\gamma_p+\lambda_p}\left(n^{*\frac{1}{1-\sigma}}w^{*1-\alpha}p_e^{*\alpha}\right)^{\gamma_p}\left(n^{\frac{1}{1-\sigma}}\phi_p^{\frac{1}{1-\sigma}}w^{1-\alpha}p_e^\alpha\right)^{\lambda_p}w^{*1-\gamma_p-\lambda_p}.
\end{aligned}
\tag{30}
$$

Outputs of final goods. They depend on the price of the final good, degrees of trade integration and labour inputs.

$$
Y_o = \frac{\left\{\begin{array}{l}[\lambda_p(\lambda_o-\lambda_p)-\gamma_p(\gamma_o-\gamma_p)+(\gamma_p+\lambda_p)(\gamma_o\lambda_p-\lambda_o\gamma_p)]\,L-(1-\gamma_p-\lambda_p)\,L^* \\ -[\sigma-\alpha(\sigma-1)(\gamma_p+\lambda_p)]\,[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2(\gamma_o\lambda_p-\lambda_o\gamma_p)]\,an\end{array}\right\}w}{(\gamma_p+\lambda_p-\gamma_o-\lambda_o)\,[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2(\gamma_o\lambda_p-\lambda_o\gamma_p)]\,p_o},
$$

$$
Y_p = \frac{\left\{\begin{array}{l}-[\lambda_o(\lambda_o-\lambda_p)-\gamma_o(\gamma_o-\gamma_p)+(\gamma_o+\lambda_o)(\gamma_o\lambda_p-\lambda_o\gamma_p)]\,L+(1-\gamma_o-\lambda_o)\,L^* \\ +[\sigma-\alpha(\sigma-1)(\gamma_o+\lambda_o)]\,[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2(\gamma_o\lambda_p-\lambda_o\gamma_p)]\,an\end{array}\right\}w}{(\gamma_p+\lambda_p-\gamma_o-\lambda_o)\,[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2(\gamma_o\lambda_p-\lambda_o\gamma_p)]\,p_p},
$$

$$Y_o^* = \frac{\left\{\begin{array}{l}\left[\lambda_p\left(\lambda_o-\lambda_p\right)-\gamma_p\left(\gamma_o-\gamma_p\right)+\left(\gamma_p+\lambda_p\right)\left(\gamma_o\lambda_p-\lambda_o\gamma_p\right)\right]L^*-\left(1-\gamma_p-\lambda_p\right)L\\-\left[\sigma-\alpha\left(\sigma-1\right)\left(\gamma_p+\lambda_p\right)\right]\left[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2\left(\gamma_o\lambda_p-\lambda_o\gamma_p\right)\right]an\end{array}\right\}w}{\left(\gamma_p+\lambda_p-\gamma_o-\lambda_o\right)\left[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2\left(\gamma_o\lambda_p-\lambda_o\gamma_p\right)\right]p_o},$$

and

$$Y_p^* = \frac{\left\{\begin{array}{l}-\left[\lambda_o\left(\lambda_o-\lambda_p\right)-\gamma_o\left(\gamma_o-\gamma_p\right)+\left(\gamma_o+\lambda_o\right)\left(\gamma_o\lambda_p-\lambda_o\gamma_p\right)\right]L^*+\left(1-\gamma_o-\lambda_o\right)L\\+\left[\sigma-\alpha\left(\sigma-1\right)\left(\gamma_o+\lambda_o\right)\right]\left[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2\left(\gamma_o\lambda_p-\lambda_o\gamma_p\right)\right]an\end{array}\right\}w}{\left(\gamma_p+\lambda_p-\gamma_o-\lambda_o\right)\left[\gamma_p-\lambda_p-\gamma_o+\lambda_o+2\left(\gamma_o\lambda_p-\lambda_o\gamma_p\right)\right]p_p}.$$

A.2 Effect of trade openness and wages and the number of domestic intermediate varieties

Interestingly, trade openness in the ordinary and processing sectors are found to have opposite effects on wages and the number of domestic intermediates that we can sign given the assumptions on the production parameters, which imply that $\gamma_o + \lambda_o < \gamma_p + \lambda_p$:

$$\frac{dw}{d\phi_o} = \frac{w}{\phi_o}\frac{\lambda_o\left(\gamma_p+\lambda_p\right)}{\left(\sigma-1\right)\left(\gamma_p+\lambda_p-\gamma_o-\lambda_o\right)} > 0, \tag{31}$$

$$\frac{dw}{d\phi_p} = -\frac{w}{\phi_p}\frac{\lambda_p\left(\gamma_o+\lambda_o\right)}{\left(\sigma-1\right)\left(\gamma_p+\lambda_p-\gamma_o-\lambda_o\right)} < 0, \tag{32}$$

$$\frac{dn}{d\phi_o} = \frac{n}{\phi_o}\frac{\lambda_o\left(1-\alpha\gamma_p-\alpha\lambda_p\right)}{\left(\gamma_p+\lambda_p-\gamma_o-\lambda_o\right)} > 0, \tag{33}$$

$$\frac{dn}{d\phi_p} = -\frac{n}{\phi_p}\frac{\lambda_p\left(1-\alpha\gamma_o-\alpha\lambda_o\right)}{\left(\gamma_p+\lambda_p-\gamma_o-\lambda_o\right)} < 0. \tag{34}$$

The intuitions for the wage results are worth mentioning. Trade openness in a final good industry (whether in the ordinary or processing sector) reduces both the price of imported varieties and the unit cost of production. This shifts production and labor to the final good whose unit cost has decreased. Since the intermediate input and labor are combined in different proportions in each final good industry, the wage rate changes to ensure that the value of the marginal labor productivity remains identical across industries (ordinary and processing). The increasing opening of trade in the ordinary industry implies a shift in production and labor from the processing industry to the ordinary industry. As the ordinary sector is more labor intensive, the wage rate increases (Equation 31). Conversely, increased trade openness in the processing industry shifts production and labor away from the ordinary industry towards the processing industry. As the latter use labor less intensively, the wage rate decreases (Equation 32).

B City-level capital stock

The initial capital stocks in 1994 (the first year investment data is available to us) in city c are calculated based on a constant (or steady state) K/Y implied by the capital-accumulation equation given a constant investment rate I/Y and constant growth rates of GDP per capita (Y/L) and population (L):

$$\left(\frac{K}{Y}\right)^c_{1994} = \frac{(Ik/Y)^c}{g+\delta+n}.$$

In this expression, K/Y is the average share of physical investment in output from 1994 through 1997, n represents average population growth over that period, and g and δ represent the average rate of total factor productivity growth and the depreciation rate, respectively. We assume $\delta = 5\%$ and $g = 2\%$, consistent with the literature. We therefore calculate:

$$K^c_{1994} = Y^c_{1994} \times \frac{(Ik/Y)^c_{1994-97}}{0.07 + n_{1994-97}},$$

where $n_{1994-97}$ is average population growth between 1994 and 1997. Given the initial capital stock estimates, the capital stock of city c in period t is given by:

$$K^c_t = \sum_{j=0}^{t} (1-\delta)^{(t-j)} Ik^c_j + (1-\delta)^t K^c_{1994},$$

with Ik^c_j being gross fixed capital formation of city c in year j.

C Additional tables and figures

Table D-1: Summary statistics

	Mean	Std dev.	Min	Max
Pollution intensities				
SO2 emission over Pop.	193.2	242.5	2.546	2749.7
SO2 emission over GDP	0.0105	0.0131	0.000272	0.161
Soot emissions over Pop	94.49	340.6	0.151	12155.9
Soot emissions over GDP	0.00535	0.0138	0.0000221	0.423
Trade variables (% of GDP)				
Trade openness	17.72	21.34	0.100	122.7
Domestic VA Trade openness	8.74	10.92	0.06	68.82
Trade openness (processing trade)	4.591	9.095	0	70.49
Trade openness (ordinary trade)	11.78	12.91	0.0992	74.87
Instruments				
ln Foreign Supplier Access	27.99	0.301	27.21	29.97
Lagged weighted export tax (processing)	0.0506	0.0392	0	0.157
Lagged weighted export tax (ordinary)	0.0604	0.0338	0.000164	0.157
Lagged weighted import tariffs	2.465	3.389	0	15.22
Controls				
Lagged GDP per capita (Yuan)	21922.6	20957.2	2217.2	212086.1
Capital Abundance (K/E) (100 billion Yuan per person)	0.0613	0.0424	0.00306	0.271
Land area per capita (km^2 per 10,000 inhabitants)	42.42	47.95	3.873	471.6
FDI over GDP	0.293	0.298	0	1.945
Share of Univ. students over population (per 10 inhabitants)	0.145	0.195	0	1.270
Technology development area	0.229	0.420	0	1
Observations		2,282		

Table D-2: The impact of trade openness on SO_2 emissions - OLS results

Dependent variable	Ln SO2 emissions per capita			
	(1)	(2)	(3)	(4)
Trade openness ([X+M]/GDP)	-0.001	-0.001		
	(0.002)	(0.002)		
Trade openness (processing trade)			0.001	0.001
			(0.003)	(0.003)
Trade openness (ordinary trade)			-0.001	-0.002
			(0.003)	(0.003)
Lagged ln GDP per capita	-0.083	-0.118	-0.087	-0.124
	(0.175)	(0.168)	(0.171)	(0.164)
Capital abundance (K/E)	-0.565	-0.451	-0.554	-0.431
	(0.874)	(0.882)	(0.869)	(0.877)
ln Land area per capita		-0.001		-0.001
		(0.002)		(0.002)
FDI over GDP		-0.035		-0.039
		(0.071)		(0.070)
Share of Univ student in population		-0.347		-0.358
		(0.290)		(0.293)
Technology development area		0.269^a		0.280^a
		(0.068)		(0.067)
Employment share in secondary sector		0.203		0.197
		(0.337)		(0.336)
ln Electricity consumption		0.097^b		0.097^b
		(0.046)		(0.046)
City and year fixed effects	Yes	Yes	Yes	Yes
No. of observations	2282	2282	2282	2282
No. of cities	234	234	234	234

Notes: Heteroskedasticity-robust standard errors appear in parentheses. ^{a}, ^{b} and ^{c} indicate significance at the 1%, 5% and 10% confidence levels.

Table D-3: The first stage of the estimates in Table 1

Dependent variable:	Trade openness				
				Domestic VA	
	(1)	(2)	(3)	(4)	(5)
ln Foreign Supplier Access	24.833^a	25.690^a	24.818^a	12.713^a	25.690^a
	(3.947)	(3.753)	(3.610)	(1.900)	(3.753)
Lagged ln GDP per capita	-3.218^c	-3.026	-26.418^c	-2.739^a	-3.026
	(1.863)	(1.958)	(15.201)	(1.049)	(1.958)
Capital abundance (K/E)	-6.629	-1.712	521.478^a	0.622	-1.712
	(11.498)	(11.425)	(180.195)	(5.438)	(11.425)
ln Land area per capita		0.047^c	0.045	0.026^b	0.047^c
		(0.027)	(0.029)	(0.013)	(0.027)
FDI over GDP		-0.083	-0.505	-0.041	-0.083
		(1.325)	(1.323)	(0.690)	(1.325)
Share of Univ student in population		-15.062^a	-12.999^a	-11.493^a	-15.062^a
		(3.155)	(3.547)	(1.940)	(3.155)
Technology development area		-10.744^a	-10.726^a	-6.494^a	-10.744^a
		(2.759)	(2.850)	(2.017)	(2.759)
Employment share in secondary sector		22.608^a	23.062^a	10.512^a	22.608^a
		(4.442)	(4.419)	(2.173)	(4.442)
ln Electricity consumption		1.661^a	1.544^a	0.916^a	1.661^a
		(0.442)	(0.433)	(0.215)	(0.442)
Lagged (ln GDP per capita)^2			1.407^c		
			(0.845)		
(K/E)^2			375.370^b		
			(149.765)		
K/E $\times$ Lagged ln GDP per capita			-58.498^a		
			(20.296)		
Observations	2282	2282	2282	2282	2282

Notes: Heteroskedasticity-robust standard errors appear in parentheses. ^{a}, ^{b} and ^{c} indicate significance at the 1%, 5% and 10% confidence levels.

Table D-4: The first stage of the estimates in columns 1 and 2 of Table 3

Column	Col 1		Col 2	
Trade-openness measure	PCS	ODT	PCS	ODT
	(1)	(2)	(3)	(4)
ln Foreign Supplier Access	17.002^a	9.101^a	16.511^a	9.453^a
	(3.059)	(2.164)	(2.961)	(2.193)
Lagged weighted export tax (ODT)	1.370	-41.530^a	3.973	-37.810^a
	(4.871)	(6.498)	(4.928)	(6.440)
Lagged weighted export tax (PCS)	-0.677	11.276^c	1.419	13.081^b
	(3.657)	(6.479)	(3.584)	(6.635)
Lagged (weighted import tariff × coast)	0.264	-0.812^a	0.312^b	-0.706^a
	(0.161)	(0.181)	(0.153)	(0.177)
Lagged ln GDP per capita	0.147	-2.641^c	0.091	-2.689^c
	(0.859)	(1.444)	(0.847)	(1.510)
Capital abundance (K/E)	-5.578	-2.638	-4.710	1.101
	(5.426)	(7.173)	(5.599)	(7.285)
ln Land area per capita			-0.003	0.040
			(0.006)	(0.024)
FDI over GDP			0.840	-0.549
			(0.934)	(0.678)
Share of Univ student in population			-2.701	-12.062^a
			(2.231)	(2.305)
Technology development area			-8.900^a	-1.590
			(1.860)	(1.580)
Employment share in secondary sector			9.175^a	6.995^b
			(2.021)	(3.042)
ln Electricity consumption			0.648^a	0.672^b
			(0.211)	(0.292)
Observations	2282	2282	2282	2282

Notes: Heteroskedasticity-robust standard errors appear in parentheses. ^{a}, ^{b} and ^{c} indicate significance at the 1%, 5% and 10% confidence levels. ODT and PCS stand for ordinary and processing, respectively.

Figure D-1: SO2 emssions per capita in 2003

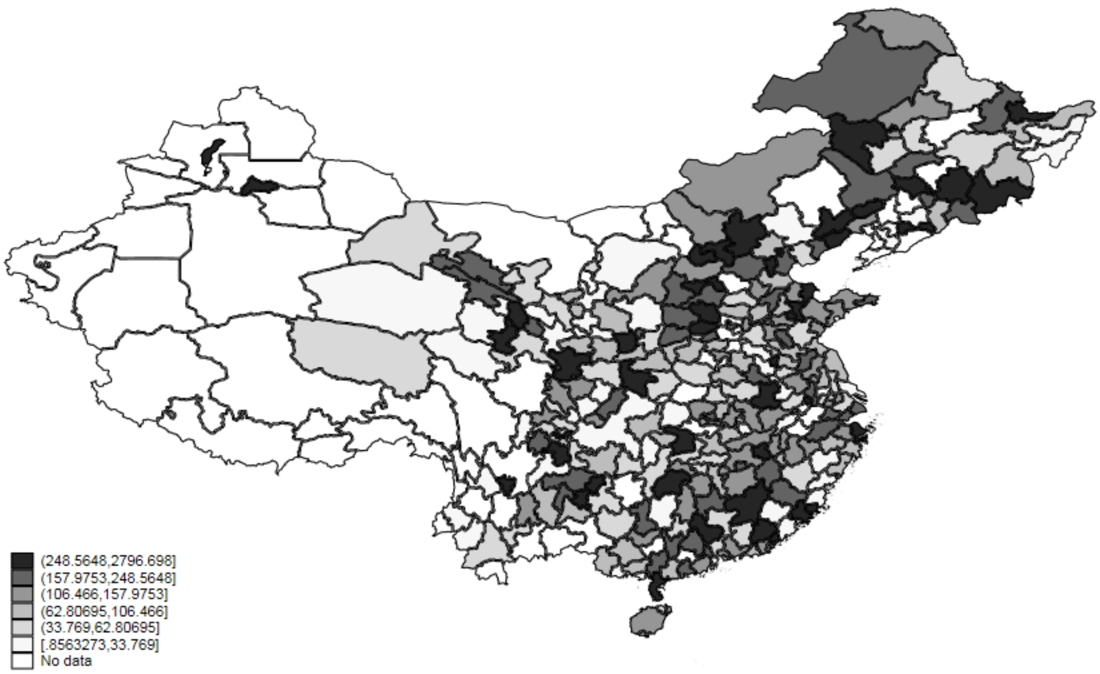

Figure D-2: Foreign supplier access - Percentage change between 2002 and 2012

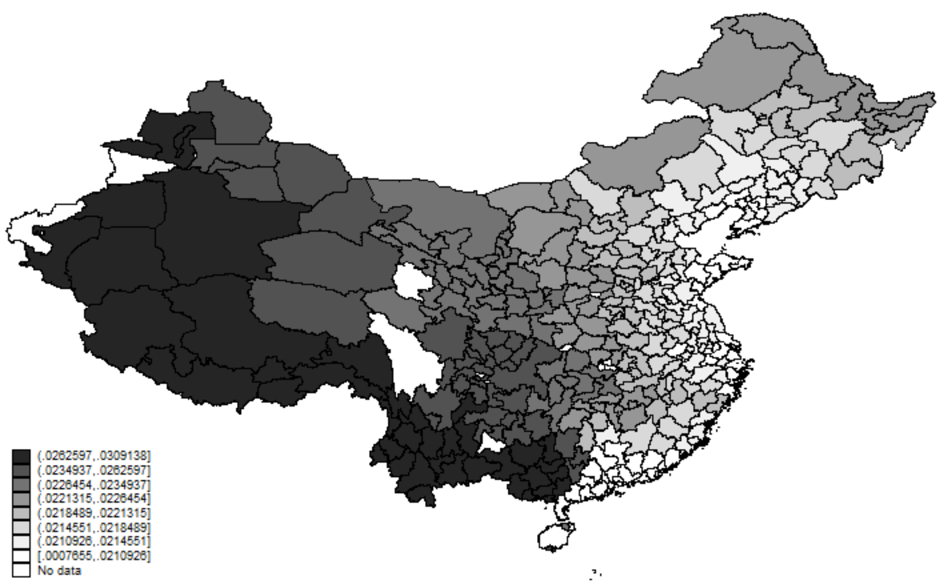

Figure D-3: Import tariffs - Percentage change between 2002 and 2012

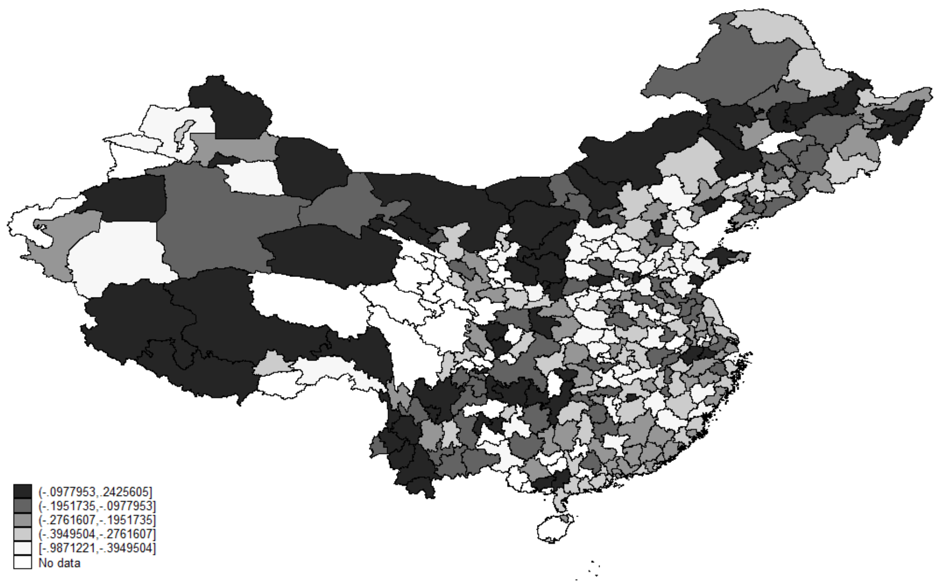

Figure D-4: Export tax - Percentage change between 2002 and 2012